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Separating secular depletion from drought: a detrended storage-deficit characterization of groundwater across Arizona’s Active Management Areas from GRACE observations (2002–2023)

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Abstract

Groundwater is an important water source in Arizona, especially during dry periods. However, groundwater loss can occur in two different ways: long-term depletion, which is a gradual loss of storage, and drought, which is a temporary shortage compared with normal conditions. These two processes are often treated as the same, even though they have different implications for water management. This study examines both processes across Arizona’s six Active Management Areas (AMAs) using groundwater storage anomalies (GWSA) from GRACE/GRACE-FO product for April 2002–December 2023 ($n = 261$ months).

We show that applying a standard drought index directly to a declining groundwater series can incorrectly classify the entire period after 2019 as drought. To address this problem, we estimate groundwater drought using a detrended Standardized Deficit Index (SDDI), evaluated with runoff, and assess long-term depletion separately using Mann–Kendall and Sen’s slope trend analysis. All six AMAs show significant groundwater storage declines, with Sen’s slopes ranging from -5.3 to -8.2 mm yr⁻¹ ($p < 0.001$). Removing the long-term trend does not eliminate drought; instead, it reveals differences in drought patterns that are hidden by the overall decline. Prescott and Phoenix experience fewer but longer and more severe drought events, with the strongest SDDI peaks reaching approximately -3.9 . Douglas, Tucson, and Santa Cruz experience more frequent but generally less severe deficits. Correlations in SDDI between AMAs (0.5–0.8) indicate that regional drought conditions are shared, although local responses differ.

Our findings show that groundwater depletion and drought should be assessed separately. Long-term trends identify areas where groundwater storage is steadily declining, while the detrended index identifies temporary drought conditions. Together, these measures provide a clearer basis for ranking groundwater risk and supporting management decisions in Arizona’s non-stationary aquifers.

Keywords: GRACE; groundwater storage anomaly; drought characterization; run theory; Mann–Kendall; Arizona; Active Management Areas

1 Introduction

Arizona depends on groundwater and water imported from the Colorado River to meet its water needs. Groundwater is becoming more important to supplement surface-water supplies as these supplies become less reliable (Castle et al., 2014; Scanlon et al., 2012). The Gravity Recovery and Climate Experiment (GRACE) and its Follow-On mission have made it possible to observe changes in terrestrial water storage over large areas (Tapley et al., 2004; Rodell et al., 2009; Famiglietti, 2014). More recently, these observations have been downscaled to increase their spatial resolution, thereby improving their usefulness for regional water management (Miro and

Famiglietti, 2018). High-resolution groundwater storage data, however, do not necessarily give a clear picture of drought. If groundwater storage is decreasing over time, a drought index derived from the original data may largely reflect the long-term decline rather than temporary drought conditions.

Groundwater depletion and drought are not synonymous, and distinguishing between them is important for water management. Depletion is a long-term decrease in groundwater storage, while drought is a temporary shortage compared with normal conditions. An aquifer can lose water steadily because of pumping, even during a year of normal rainfall. Likewise, an aquifer with a small long-term decline may still experience a severe drought. If these two processes are combined, it is difficult to distinguish between a chronic water-storage problem and a temporary drought. For instance, a standardized index derived from a strongly declining groundwater record can remain negative for many years, making individual drought events difficult to identify (McKee et al., 1993). This may result in misleading interpretations when comparing groundwater stress between different areas.

This study explores groundwater depletion and drought in Arizona’s six Active Management Areas (AMAs) using the groundwater storage anomaly (GWSA) product. We consider a practical question: which AMAs are losing groundwater at the fastest rate, and how do their rankings change if drought is considered separately from long-term depletion? We first estimate long-term groundwater storage trends using robust nonparametric statistical methods. Second, we compute a detrended Standardized Deficit Index (SDDI) and apply run theory to identify drought events and assess their duration, severity, and frequency (Yevjevich, 1967). Third, we estimate cumulative groundwater depletion using a maximum-depletion operator, following the general approach of storage-deficit analysis by Thomas et al. (2014). Finally, we compare the depletion and drought rankings to identify the different types of groundwater stress experienced by the AMAs.

The key contribution of this study is a practical method to distinguish long-term groundwater depletion from temporary drought. We do not introduce a new drought index, but rather use existing methods to provide a clearer understanding of how groundwater storage has changed. This distinction can help water managers determine where long-term measures are needed to reduce groundwater depletion and where short-term drought responses may be necessary.

2 Data and Methods

2.1 Groundwater storage anomaly data

Monthly groundwater storage anomaly (GWSA) data were obtained for Arizona’s six Active Management Areas (AMAs): Prescott, Phoenix, Pinal, Tucson, Douglas, and Santa Cruz. The data were extracted as area averages from GRACE/GRACE-FO GWSA product developed in the companion study. The study period covers April 2002 to December 2023, comprising 261 months of data with no missing months after gap-filling. GWSA is expressed as equivalent water thickness in millimeters relative to the product’s baseline. The original terrestrial water storage anomaly (TWSA) data are based on the CSR mascon solution (Save et al., 2016). Soil moisture and snow storage were then subtracted to estimate groundwater storage (Rodell et al., 2018). Because the data are derived from GRACE, all analyses in this study refer to groundwater storage changes at the AMA scale. Independent validation with ADWR monitoring wells and the U.S. Drought Monitor is not included in this index study and is discussed as a limitation in Section 4.1.

2.2 Trend estimation

Secular depletion was quantified per AMA with (i) ordinary least squares on the monthly series and (ii) the nonparametric Mann–Kendall test (Mann, 1945) with the Theil–Sen slope estima-

tor (Sen, 1968), which is robust to non-normal residuals and outliers. Slopes are reported in mm yr^{-1} ; significance at $\alpha = 0.05$.

2.3 Detrended standardized deficit index (SDDI)

To measure drought as a departure from the evolving baseline rather than from a fixed long-term mean, we removed the fitted linear trend from each AMA series and standardized the residual:

$$\text{SDDI}_i(t) = \frac{r_i(t) - \bar{r}_i}{\sigma_{r_i}}, \quad r_i(t) = x_i(t) - (\hat{a}_i + \hat{b}_i t), \quad (1)$$

where $x_i(t)$ is GWSA for AMA i and $\hat{a}_i + \hat{b}_i t$ is its OLS trend. $\text{SDDI} = 0$ is the trend-adjusted normal; values ≤ -1 and ≤ -1.5 denote moderate and severe deficit, following the standardized convention of McKee et al. (1993). For contrast we also computed the *naive* index—a 12-month rolling mean z-scored over the full record—to demonstrate trend contamination.

2.4 Cumulative depletion (drawdown) operator

As a monotone-storage complement we computed the drawdown from the running maximum,

$$D_i(t) = x_i(t) - \max_{\tau \leq t} x_i(\tau) \leq 0, \quad (2)$$

which measures how far current storage sits below the highest level previously attained—a cumulative, non-recovering depletion signature.

2.5 Run-theory drought characterization

Drought events were extracted from SDDI by Yevjevich run theory (Yevjevich, 1967) with truncation level 0. A run (consecutive months with $\text{SDDI} < 0$) was retained as a drought only if its minimum reached ≤ -1 . For each event we recorded duration (months), severity (the positive area $-\sum(\text{SDDI})$ below truncation, in σ -months), and peak intensity (the minimum SDDI). Per AMA we aggregated event count, mean/maximum duration, total severity and worst peak, plus the counts of moderate and severe months.

2.6 Ranking and spatial coherence

AMAs were ranked independently by (a) depletion (Sen’s slope) and (b) drought (total SDDI severity), and the two orderings were compared. Inter-AMA SDDI correlations quantified the shared regional signal versus basin-specific response.

3 Results

3.1 Widespread and significant groundwater depletion

During the study period, all six AMAs experienced groundwater storage loss (Table 1). Mean GWSA ranged from -46.9 to -63.7 mm, with minimum values approaching -195 mm. The Mann–Kendall test showed significant decreasing trends in all six AMAs ($p < 0.001$; Table 2). Similarly, Sen’s slope estimates ranged from -5.3 mm yr^{-1} in Phoenix to -8.2 mm yr^{-1} in Douglas. The OLS and Sen’s slope estimates differed by less than 0.3 mm yr^{-1} , suggesting that the trends were not strongly influenced by outliers. The raw and fitted trends are shown in Figure 1. Groundwater storage showed little seasonal variation relative to the long-term decline (Figure 2), with storage generally reaching its highest levels in late winter or early spring and declining during the dry period before summer.

Table 1: Descriptive statistics of AMA GWSA (mm), April 2002–December 2023.

AMA	N	Mean	SD	Min	Max
Prescott	261	−59.49	51.69	−183.69	46.40
Phoenix	261	−46.86	37.91	−143.81	16.52
Pinal	261	−47.21	41.73	−154.41	15.68
Tucson	261	−48.43	41.54	−150.53	20.26
Douglas	261	−63.69	58.26	−194.58	18.30
Santa Cruz	261	−54.18	45.47	−162.49	16.47

Table 2: Trend statistics per AMA (sorted by Sen’s slope). All trends are significant at $p < 0.001$.

AMA	OLS (mm/yr)	Sen (mm/yr)	MK τ	Trend
Douglas	−8.42	−8.22	−0.72	decreasing
Prescott	−6.93	−7.12	−0.64	decreasing
Santa Cruz	−6.34	−6.24	−0.67	decreasing
Tucson	−5.95	−5.80	−0.74	decreasing
Pinal	−5.99	−5.79	−0.73	decreasing
Phoenix	−5.38	−5.26	−0.71	decreasing

3.2 Trend contamination of a naive index

Figure 3 compares the two drought indices for Phoenix. The index calculated from the full groundwater record (panel a) shows a continuous downward trend and reaches the severe drought threshold only after 2019. However, this does not necessarily mean that 2019–2023 was more unusual than earlier periods. Instead, the index mainly reflects the long-term decline in groundwater storage. In contrast, the detrended SDDI (panel b) fluctuates around zero and identifies separate drought events in 2003–2004, 2014, 2018, and 2021–2023, with periods of recovery between them. Therefore, a drought ranking based on the original, non-detrended index would mainly rank the AMAs by their long-term storage trends, repeating the results in Table 2 rather than providing a separate measure of drought.

3.3 Drought events and their character

The drought event statistics calculated from the SDDI are presented in Table 3. Figure 6 shows the relationship between drought severity and duration, with bubble size representing peak intensity. The drought calendar (Figure 4) shows that drought conditions became more frequent after approximately 2018, although the timing of individual events differed among the AMAs.

Two main drought patterns were identified. Prescott and Phoenix experienced fewer drought events, with 10 events each, but these events tended to last longer and reach greater severity. Their longest events lasted 8.8 and 8.2 months, respectively, and Prescott recorded the lowest SDDI value of −3.99. This pattern can be described as fewer but longer and more severe droughts. In contrast, Douglas, Tucson, and Santa Cruz experienced more frequent droughts, with 16 events each, but the events were generally shorter and less severe. Despite these differences, Douglas had the highest total drought severity (103.2 standard-deviation months), followed by Prescott (98.6 standard-deviation months).

3.4 Depletion vs drought rankings

Table 4 compares the groundwater depletion and drought rankings. The two rankings agree for the most stressed AMAs: Douglas, Prescott, and Santa Cruz rank among the top three when either long-term depletion rate or drought severity is considered. This agreement indicates that these AMAs face both substantial long-term groundwater loss and severe drought conditions.

Monthly groundwater storage anomaly by Arizona AMA (2002–2023)

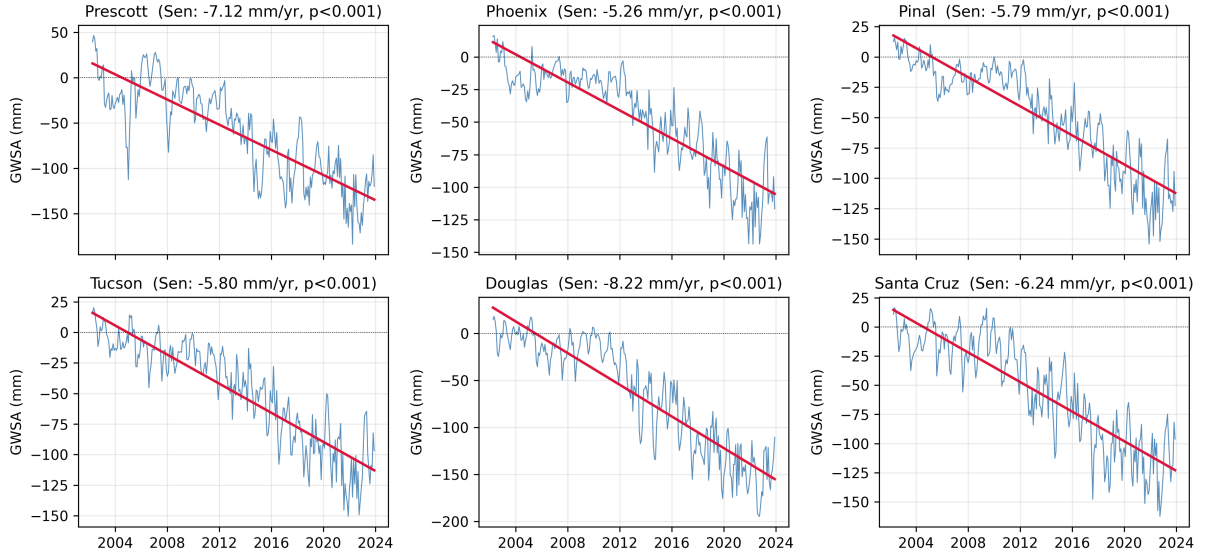


Figure 1: Monthly GWSA (blue) and fitted OLS trend (red) for the six AMAs. Sen’s slope and Mann–Kendall significance are annotated per panel.

Table 3: Drought-event characteristics from SDDI run theory (truncation 0, retained if peak ≤ -1), sorted by total severity. “Sev. months” counts SDDI ≤ -1.5 .

AMA	Events	Mean dur. (mo)	Max dur. (mo)	Total sev. (σ -mo)	Worst peak (σ)	Sev. months
Douglas	16	7.31	32	103.25	-2.33	18
Prescott	10	8.80	25	98.59	-3.92	17
Santa Cruz	16	6.75	29	96.33	-2.99	19
Tucson	16	6.31	23	93.55	-2.74	19
Phoenix	10	8.20	26	90.85	-2.87	18
Pinal	10	8.00	21	81.70	-3.03	18

However, the rankings differ for the other AMAs. Phoenix has the slowest groundwater depletion rate, ranking sixth according to Sen’s slope, but ranks fifth in drought severity, above Pinal. This is because Phoenix experiences longer and deeper drought events after the long-term trend is removed (Figure 7). These differences show that groundwater depletion and drought do not always affect the same areas in the same way, and that both measures are needed to understand groundwater stress.

3.5 Shared regional signal

Inter-AMA SDDI correlations range 0.5–0.8 (Fig. 8), strongest among the geographically proximate southern basins (Tucson, Santa Cruz, Douglas) and weakest between the northern Prescott basin and the rest. This is consistent with a common regional drought forcing modulated by basin-specific recharge and abstraction, and supports treating the AMAs as a coupled but not identical set.

4 Discussion

The primary methodological conclusion is that it is important to detrend a groundwater storage-based drought index when groundwater storage has a strong long-term decline. Without detrend-

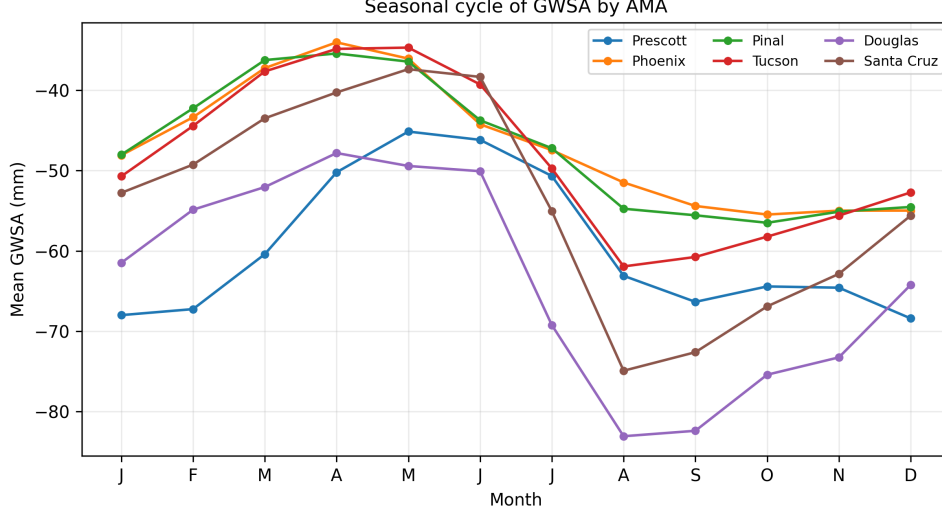


Figure 2: Mean monthly (climatological) GWSA by AMA. The seasonal amplitude is small relative to the multi-decadal decline in Table 2.

Table 4: Depletion vs drought ranking (1 = most stressed).

AMA	Sen (mm/yr)	Total sev.	Max drawdown (mm)	Depl. rank	Drought rank
Douglas	-8.22	103.25	-212.9	1	1
Prescott	-7.12	98.59	-230.1	2	2
Santa Cruz	-6.24	96.33	-179.0	3	3
Tucson	-5.80	93.55	-170.8	4	4
Pinal	-5.79	81.70	-170.1	5	6
Phoenix	-5.26	90.85	-160.3	6	5

ing, the standard index may simply reflect the continued decrease in groundwater storage rather than identify unusually dry periods. This can lead to a misleading drought ranking that closely follows the long-term depletion trend, as illustrated in Figure 3a. It can also create a false impression of the relationships between different groundwater indices. Separating the long-term trend from temporary changes helps avoid this problem.

The results also show that detrending does not completely change which AMAs are most stressed. Douglas, Prescott, and Santa Cruz remain among the most affected areas when both depletion and drought are considered. Detrending, however, reveals important differences in the types of drought experienced by each AMA. Prescott and Phoenix experience fewer but longer and deeper droughts, whereas Douglas, Tucson, and Santa Cruz experience more frequent droughts. These differences are important for water management. Regions that experience frequent droughts may need measures to manage repeated water shortages, while regions with longer and more intense droughts may need additional water supplies or emergency drought plans. Detrending also changes the interpretation of Phoenix. Although Phoenix has the slowest long-term depletion rate, it is not the least affected by drought when its severe 2021–2023 event is considered separately.

Another useful perspective for groundwater management is provided by the cumulative-depletion analysis. Prescott and Douglas have experienced the largest declines below their previously observed groundwater storage levels, indicating that storage has not fully recovered. This information can help managers understand how far an aquifer has declined from earlier storage conditions or management targets. The SDDI, Sen’s slope, and cumulative-depletion measures can be combined to provide a more comprehensive understanding of groundwater stress. The SDDI represents temporary drought conditions, Sen’s slope represents the long-

Trend contamination of a standardized index — Phoenix

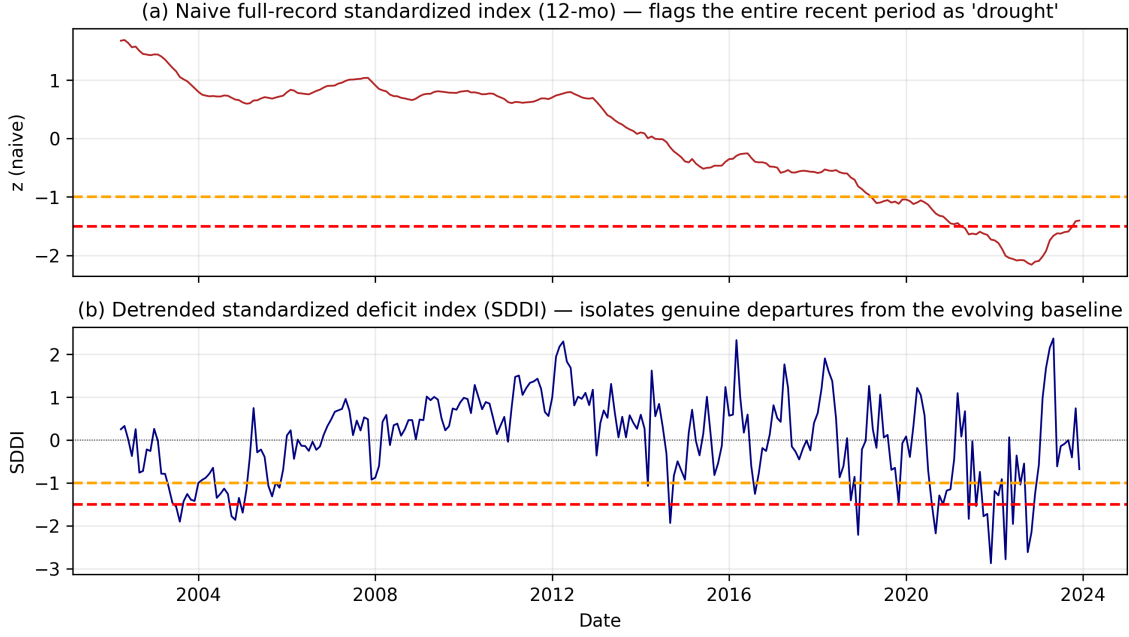


Figure 3: Trend contamination (Phoenix). (a) Naive full-record standardized index; (b) detrended standardized deficit index (SDDI). Dashed lines mark moderate (-1) and severe (-1.5) thresholds.

term rate of storage loss, and cumulative depletion describes the accumulated storage deficit. Together, these measures are more informative than any one of them alone.

4.1 Limitations

This study has three main limitations. First, the groundwater storage data are derived from GRACE. Therefore, the results represent groundwater storage changes at the AMA scale rather than changes in individual aquifers within each AMA. Independent validation using ADWR monitoring wells and U.S. Drought Monitor categories is needed before the results can be used for operational decisions. This validation will be addressed in the companion index study.

Second, averaging the data across each AMA may mask local variations in groundwater storage. The 1 km product offers higher spatial resolution; however, areas with larger groundwater deficits may be averaged together with areas showing smaller deficits. Furthermore, the SDDI assumes that the long-term trend was approximately linear during 2002–2023. If the rate of groundwater depletion changes over time or follows a nonlinear pattern, a piecewise or nonlinear detrending method may be more appropriate.

Finally, this study describes groundwater depletion and drought without identifying their causes. Further analysis is needed to understand how these patterns are related to climate, groundwater pumping, land use, and other human activities. This type of attribution is beyond the scope of this study and is addressed through a separate explanatory-modeling framework.

5 Conclusions

This study analyzed groundwater depletion and drought across Arizona’s six Active Management Areas (AMAs) using GRACE-based groundwater storage data. Groundwater storage decreased significantly over time in all six AMAs, with Sen’s slopes ranging from -5.3 to -8.2 mm yr $^{-1}$ ($p < 0.001$). The results also show that a standard drought index calculated from groundwater

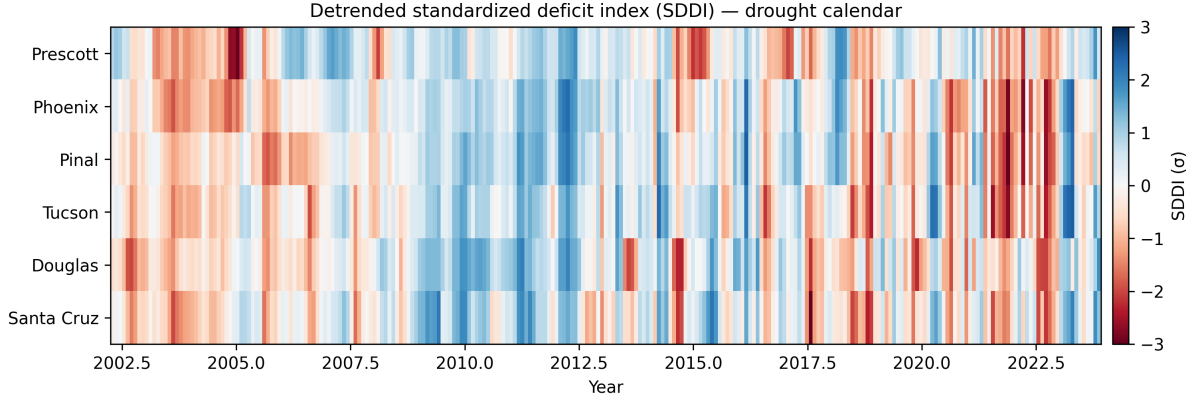


Figure 4: SDDI drought calendar (AMA $\times$ time). Blue denotes deficit below the trend-adjusted normal; the post-2018 band shows coherent regional intensification.

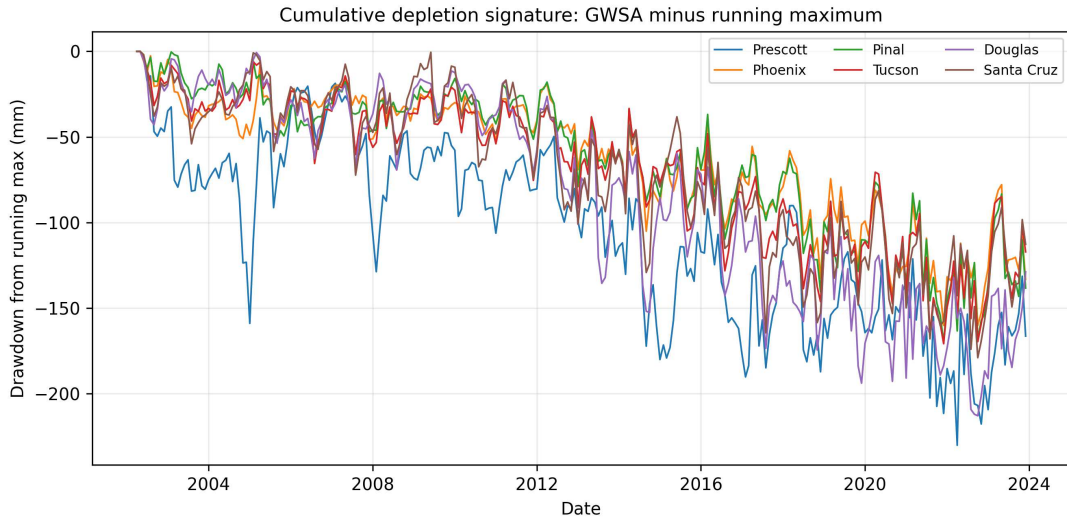


Figure 5: Drawdown from the running maximum, $D_i(t)$. The non-recovering descent quantifies cumulative depletion; Prescott and Douglas reach the deepest drawdowns (< -210 mm).

data with a strong negative trend may mainly reflect the long-term decline. Removing this trend is therefore important for distinguishing temporary drought conditions from long-term groundwater depletion.

According to the detrended Standardized Deficit Index (SDDI) and run-theory analysis, Douglas, Prescott, and Santa Cruz remain among the most stressed AMAs in terms of both depletion and drought. However, drought patterns vary among the AMAs. Prescott and Phoenix experience fewer but longer and more intense droughts, while Douglas, Tucson, and Santa Cruz experience more frequent but generally shorter droughts. These differences show that groundwater systems experience different types of stress and may therefore require different management approaches.

Groundwater depletion, drought, and cumulative storage loss provide complementary information. Depletion trends indicate the long-term rate of groundwater loss, the SDDI identifies temporary drought conditions, and cumulative depletion shows how far groundwater storage has declined from previous levels. Reporting these measures together provides a clearer understanding of groundwater stress than relying on a single measure.

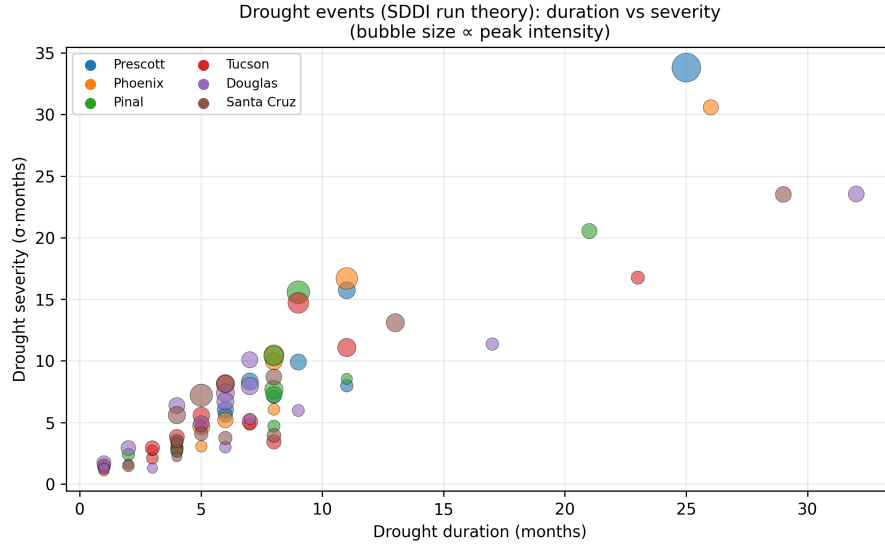


Figure 6: Drought-event severity vs duration by AMA; bubble size scales with peak intensity. The episodic-deep (Prescott, Phoenix) and frequent-shallow (Douglas, Tucson, Santa Cruz) regimes are visible.

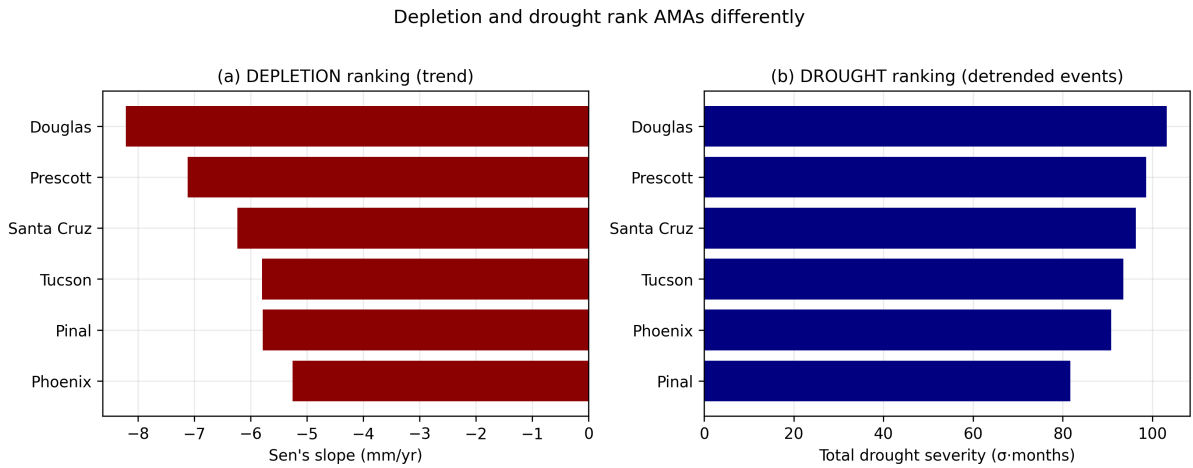


Figure 7: AMA rankings by (a) depletion (Sen's slope) and (b) drought (total SDDI severity). Leading basins agree; Phoenix and Pinal swap in the middle.

Declarations

Funding. This study did not receive dedicated external funding.

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Ethics approval. Not applicable.

Consent to participate. Not applicable.

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Data availability. The groundwater storage anomaly data analyzed in this study were obtained from GRACE/GRACE-FO terrestrial water storage data, which are publicly available through the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC). The processed AMA-level groundwater storage time series and the data used to calculate the drought and depletion indices are available from the corresponding author on reasonable request.

Author contributions. Md Rayhan conceived the study, processed and analysed the data,

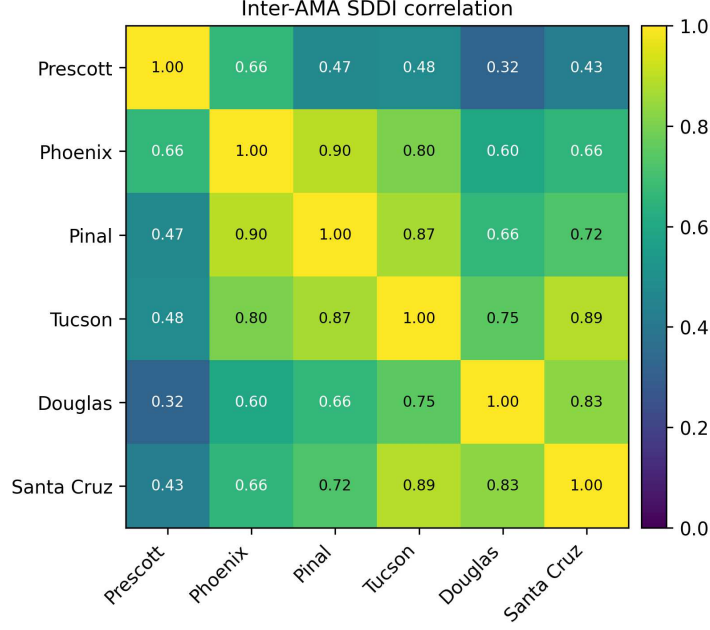


Figure 8: Inter-AMA SDDI correlation matrix.

developed the drought and depletion analysis, prepared the figures, and wrote and revised the manuscript. The author read and approved the final manuscript.

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